Design and Development of Fuzzy Logic Controller for Flow Control of Dams

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Abstract
In this paper, rule base and membership function based on fuzzy logic is proposed for reservoir control of dam. To demonstrate the performance of the proposed system, this model simulates the control system using difference method and rule. The rule base and membership functions have a great influence on the performance and efficacy of the plant and also to optimize the hydro power generation in the high altitude region. FLC method for turbine valve to control the water flow through turbine for hydro power generation. Thus it shows overall effective control and operation of the mechanical equipment’s in a hydroelectric power generation project with FLC and its usefulness. The hardware of control system for fuzzifiers and defuzzifiers can be designed according to the need of system. This research used “Fuzzy Method” and “Mamdani Inference Method” to evaluate using manual “C.O.G. Defuzzification” and MATLAB FIS editor validation. In this design two input parameters: water level and flow rate and two output parameters: release control valve and drain valve are used.

Keywords – Fuzzy logic controller, Fuzzy logic Toolbox, Flow and Level Control, Valve Control, Hydro-Electric Power Plant

1. Introduction
Dams were constructed for the electric power generation, flood control, irrigation system, metropolitan and industrial water supply. Different kind of methods have been introduced and implemented to control the hydroelectric power dam due to non-deterministic behavior of water parameters such as flow rate and release etc. In a hydroelectric power generation project, consumers require power relied on water level and flow rate. To maintain these parameters within the prescribed limits, various controls are required. Power can be controlled by controlling flow through turbine and dams are maintained safely through controlling spillway gates. The development of a hydro-electric power dam control system based on fuzzy logic with two inputs and two outputs. Using water level and flow rate measuring devices for feedback control, and two control elements for draining and controlling valve. Water level and flow rate has been achieved by formulating fuzzy rules.

2. Basic structure of the proposed hydro-electric power dam
Fig. 1 shows the main parts of the proposed hydro-electric power plant. Water in upper lake pass through the penstock. The water travel through a large pipe called penstock. Controllers are used to adjust dam lake level in set point only within shortest time by adjusting valve openness. Sensors are used to detect water level and flow rate. In this paper, ultrasonic sensors were selected.

Figure 1 Arrangement of proposed hydro-electric power system

An ultrasonic sensor transmits ultrasonic waves into the air and detects reflected waves from an object. Water release control valve generates electricity. The force of water spins the turbine. Inside the generator, that creates an electric field and producing electricity. Water on releasing from the dam gets to the blades of the turbine all the way through the penstock. Its slope and thickness determines the efficiency of the dam. Required power related water level and flow rate. The greater the vertical distance between the upper and lower lakes, the more is the generation of electricity. Water flow out of the penstock flows into the lower lake. The drain valve control can be utilized further for land irrigation according to the need.
Figure 2 Flow chart of controller system

Output Power:
The power available is proportional to the product of head and flow rate. The general formula for any hydro system’s power output is:

\[ P = \eta \rho g Q H \]

- \( P \) = mechanical power produced at the turbine shaft (Watts)
- \( \eta \) = hydraulic efficiency of the turbine
- \( \rho \) = density of water (1000 kg/m³)
- \( g \) = acceleration due to gravity (9.81 m/s²)
- \( Q \) = volume flow rate passing through the turbine (m³/s)
- \( H \) = effective pressure head of water across the turbine (m)

This equation is derived from the general Bernoulli equation used to estimate flow through an underflow gate:

\[ Q = a L C_q \sqrt{2gh} \]

Where:
- \( Q \) = discharge
- \( C_q \) = discharge coefficient

3. Materials & methods

River, reservoir, dam with spillway gates, penstock, flow control-turbine valves, hydro turbine, generator and draft tube are the main components of hydro-electric power plant. Dam with spillway gates and reservoir is also necessary for the flood control, irrigation system, tourism and public water supply other than power generation. Water passed through penstock, a flow control-turbine valve is used for power generation in hydro turbine. Turbine produces electrical energy through generator and then the water is released to downstream side. Fuzzy rule base control for both control valve and drain valve and then simulating their operation in a synchronized way.

3.1 Fuzzy logic controller

Fuzzy Logic Controller is an attractive choice when precise mathematical formulations are not possible. Other advantages are:

1. It can work with less precise inputs.
2. It doesn’t need fast processors.
3. It needs less data storage in the form of membership functions and rules than conventional look up table for nonlinear controllers.
4. It is more robust than other non-linear controllers.

There are three principal elements to a fuzzy logic controller:

a. Fuzzification module (Fuzzifier)

b. Rule base and Inference engine

c. Defuzzification module (Defuzzifier)

Figure 3 Block Diagram of Hydro-Electric Power Dam fuzzy control system
Control Valve: The application of FLC system for dam consisting of two input variables: “Dam Lake Level” and “Water Inflow Rate”, “Openness of the Control Valve” is output variable and is controlled by the FLC rule base. The main aim of this control problem is to discharge excess water (danger level or above) in shortest possible time for the overall safety of the system and thus bringing it back to safe or desired level (below danger level) through FLC. Five triangular membership functions are determined over a scale range of -1m to 1m for the water level and -0.1(m^3-s) to 0.1(m^3-s) for flow rate inputs. The control valves output variables consist of five membership functions: closed fast, closed slow, no change, opened slow, opened fast.

Drain Valve: The algorithm designed for this system consists of two fuzzy input variables: “Water Level” and “Flow Rate” and one output variable “Drain Valve”. The main aim of this control problem is to regulate the flow of water being fed to the turbine in accordance with the load perturbations and thereby maintaining the constant output frequency of the system at the desired level through FLC. A scale range of -1m to 1m for the water level and -0.1(m^3-s) to 0.1(m^3-s) for flow rate inputs. The control valves output variables consist of five membership functions: closed fast, closed slow, no change, opened slow, opened fast.

### Table 1. Membership Functions And Ranges of Input Variable Water Level (m)

<table>
<thead>
<tr>
<th>Membership Function(MF)</th>
<th>Ranges</th>
<th>Region Occupied</th>
</tr>
</thead>
<tbody>
<tr>
<td>Above Danger</td>
<td>-2:0</td>
<td>1</td>
</tr>
<tr>
<td>Danger</td>
<td>-1:0</td>
<td>1-2</td>
</tr>
<tr>
<td>Below Danger</td>
<td>-0.5:0.5</td>
<td>2-3</td>
</tr>
<tr>
<td>Low</td>
<td>0:1</td>
<td>3-4</td>
</tr>
<tr>
<td>Very Low</td>
<td>0:2</td>
<td>4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Membership Function(MF)</th>
<th>Ranges</th>
<th>Region Occupied</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very Slow</td>
<td>-0.2:0</td>
<td>1</td>
</tr>
<tr>
<td>Slow</td>
<td>-0.1:0</td>
<td>1-2</td>
</tr>
<tr>
<td>Normal</td>
<td>-0.05:0.05</td>
<td>2-3</td>
</tr>
<tr>
<td>Fast</td>
<td>0:0.1</td>
<td>3-4</td>
</tr>
<tr>
<td>Very Fast</td>
<td>0:0.2</td>
<td>4</td>
</tr>
</tbody>
</table>

Fuzzy Set characterizing the Input:
Use triangular membership function types for the input. The five membership functions, “Above Danger”, “Danger”, “Below danger”, “Low” and “Very Low” are used to show the various ranges of input fuzzy variable “WATER LEVEL” in a plot consisting of four regions as shown in Figure 5.

![Figure 5 Membership Functions of Input Variable Water Level](image)

The membership function has a triangular shape. The five membership functions, “Very Slow”, “Slow”, “Normal”, “Fast” and “Very Fast” are used to show the various ranges of input fuzzy variable “FLOW RATE” in a plot consisting of four regions as shown in Figure 6.
Two input variables of fuzzification process need two separate fuzzifier. Figure show the design of a fuzzifier.

Table 3. Show the result of fuzzification

<table>
<thead>
<tr>
<th>Input Variables</th>
<th>Values</th>
<th>Region Selection</th>
<th>Fuzzy Set Calculation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water Level</td>
<td>x=0.4</td>
<td>0.4&lt;x&lt;0.5</td>
<td>F₁=(0.5-0.4)/0.2=0.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Region 3</td>
<td>F₂=1-F₁=1-0.5=0.5</td>
</tr>
<tr>
<td>Flow Rate</td>
<td>x=0.09</td>
<td>0.1&lt;x&lt;0.09</td>
<td>F₃=(0.1-0.09)/0.02=0.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Region 4</td>
<td>F₄=1-F₃=1-0.5=0.5</td>
</tr>
</tbody>
</table>

3.4 Fuzzy Rule

Number of active rules = mn

Where m = maximum number of overlapped fuzzy sets and n= number of inputs.

For this design, m = 5 and n = 2, so the total number of active rules are 25. The total number of rules is equal to the product of number of functions accompanied by the input variables in their working range. The two input variables described here consisted of five membership functions. Thus, 5 x 5 = 25 rules were required which are shown in Table 4 and 5.

Table 4. Total Number of Rules for Control Valve

<table>
<thead>
<tr>
<th>Flow Rate Water level</th>
<th>Very Slow</th>
<th>Slow</th>
<th>Normal</th>
<th>Fast</th>
<th>Very Fast</th>
</tr>
</thead>
<tbody>
<tr>
<td>Above Danger</td>
<td>Closed</td>
<td>Closed</td>
<td>Closed</td>
<td>Closed</td>
<td>Open</td>
</tr>
<tr>
<td>Danger</td>
<td>Closed</td>
<td>Closed</td>
<td>Closed</td>
<td>Closed</td>
<td>No Change</td>
</tr>
<tr>
<td>Below Danger</td>
<td>Open</td>
<td>No Change</td>
<td>Closed</td>
<td>Closed</td>
<td>Closed</td>
</tr>
<tr>
<td>Low</td>
<td>Opened</td>
<td>Opened</td>
<td>Opened</td>
<td>Opened</td>
<td>Opened</td>
</tr>
<tr>
<td>Very Low</td>
<td>Opened</td>
<td>Opened</td>
<td>Opened</td>
<td>Opened</td>
<td>Opened</td>
</tr>
</tbody>
</table>

Table 5. Total Number of Rules for Drain Valve

<table>
<thead>
<tr>
<th>Flow Rate Water level</th>
<th>Very Slow</th>
<th>Slow</th>
<th>Normal</th>
<th>Fast</th>
<th>Very Fast</th>
</tr>
</thead>
<tbody>
<tr>
<td>Above Danger</td>
<td>Closed</td>
<td>Closed</td>
<td>Closed</td>
<td>Open</td>
<td>Open</td>
</tr>
<tr>
<td>Danger</td>
<td>Open</td>
<td>Opened</td>
<td>Opened</td>
<td>No Change</td>
<td>No Change</td>
</tr>
<tr>
<td>Below Danger</td>
<td>No Change</td>
<td>No Change</td>
<td>Closed</td>
<td>Closed</td>
<td>Opened</td>
</tr>
<tr>
<td>Low</td>
<td>Opened</td>
<td>Opened</td>
<td>Opened</td>
<td>Opened</td>
<td>Opened</td>
</tr>
<tr>
<td>Very Low</td>
<td>Opened</td>
<td>Opened</td>
<td>Opened</td>
<td>Opened</td>
<td>Opened</td>
</tr>
</tbody>
</table>

3.5 Inference engine

The inference engine involves four AND operators that select minimum input value for the output. Four inputs (F) of fuzzifier were accepted by inference engine and applied the min-max composition to obtain the output values (R).

R1= f₁ ^ f₃ =0.5
R2= f₁ ^ f₄ =0.5
R3= f₂ ^ f₃ =0.5
R4= f₂ ^ f₄ =0.5
3.6 Rule Selector

Two crisp values of water level and flow rate were received by the rule selector. That gives singleton values of output functions under algorithm rules applied on design model. To find the corresponding singleton values (S1, S2, S3, and S4), four rules are needed for each variable according to these rules are listed in Table 6 and figure 9.

Table 6. Illustration of Rules Applied Model

<table>
<thead>
<tr>
<th>Rule No</th>
<th>INPUTS</th>
<th>SINGLETON VALUES OF OUTPUTS</th>
<th>Singleton Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water Level</td>
<td>Flow Rate</td>
<td>Release Control Valve</td>
<td>Drainage Valve</td>
</tr>
<tr>
<td>1</td>
<td>Below Danger</td>
<td>Fast</td>
<td>25% Opened =0.25</td>
</tr>
<tr>
<td>2</td>
<td>Below Danger</td>
<td>Very Fast</td>
<td>25% Opened =0.25</td>
</tr>
<tr>
<td>3</td>
<td>Low</td>
<td>Fast</td>
<td>Fully Opened =1.00</td>
</tr>
<tr>
<td>4</td>
<td>Low</td>
<td>Very Fast</td>
<td>Fully Opened =1.00</td>
</tr>
</tbody>
</table>

3.7 Deffuzifier

Use triangular membership function types for the output. First, set the range (and the Display Range) to (-1 1), to cover the output range. Initially, the closed fast membership function will have the parameters (-1 -0.9 -0.8), the closed slow membership function will be (-0.6 -0.5 -0.4), for the no change membership function will be (-0.1 0 0.1), the opened slow membership function will be (0.2 0.3 0.4), the opened fast membership function will be (0.8 0.9 1) as shown in figure 10.

3.8 Fuzzy Set Characterizing output:

After estimating its inputs, the defuzzification process provides the crisp value outputs. Four values of R1, R2, R3, R4 from the outputs of inference engine and four values S1, S2, S3, and S4 from the rule selector are inputs of defuzzifier as shown in Fig. 11. There are many methods of Defuzzifier, the center of average (C.O.A) method was used in this system to estimates the crisp value output. Each output variable membership function plot consists of five triangular functions for simplification.

Table 7. Membership Functions And Ranges of Output Variables

<table>
<thead>
<tr>
<th>Membership Function(MF)</th>
<th>Ranges</th>
<th>Control Valve</th>
<th>Drain Valve</th>
</tr>
</thead>
<tbody>
<tr>
<td>MF1</td>
<td>-1:0.8</td>
<td>Closed Fast</td>
<td>Closed Fast</td>
</tr>
<tr>
<td>MF2</td>
<td>-0.6:0.4</td>
<td>Closed Slow</td>
<td>Closed Slow</td>
</tr>
<tr>
<td>MF3</td>
<td>-0.1:0.1</td>
<td>No-Change</td>
<td>No-Change</td>
</tr>
<tr>
<td>MF4</td>
<td>0.2:0.4</td>
<td>Opened Slow</td>
<td>Opened Slow</td>
</tr>
<tr>
<td>MF5</td>
<td>0.8:1</td>
<td>Opened Fast</td>
<td>Opened Fast</td>
</tr>
</tbody>
</table>

3.11 Figure 8 Block Diagram of Inference Engine

3.12 Figure 9 Rule Base

3.13 Figure 10 Triangular Membership Functions of Output Variable for Drain Valve & Control Valve
3.9 Advantages of Triangular Membership Functions
The general membership functions under consideration are Triangular, Trapezoidal, Gaussian, bell, sigmoidal and polynomial types. Fuzzy controller sensitivity has been analyzed and compared for different membership functions with the help of MATLAB Fuzzy Logic Toolbox where the triangular function was taken as the base in each case for comparison. The result of triangular MF gives the best drive performance and the trapezoidal MF response is very close to that of triangular MF. Triangular MF, consists of simple straight line segments, is very easy to implement in fuzzy logic controller.

4. Results and discussion
The designed values for two outputs, Control Valve and Drain Valve are shown in the Table 8 and Table 9. According to the results of inference engine:

\[ \sum R_i = R_1 + R_2 + R_3 + R_4 = 0.5 + 0.5 + 0.5 + 0.5 = 2 \]

Table 8. Design value for Control Valve

<table>
<thead>
<tr>
<th>i</th>
<th>( R_i )</th>
<th>( S_i )</th>
<th>( R_i \cdot S_i )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.5</td>
<td>0.25</td>
<td>0.125</td>
</tr>
<tr>
<td>2</td>
<td>0.5</td>
<td>0.25</td>
<td>0.125</td>
</tr>
<tr>
<td>3</td>
<td>0.5</td>
<td>1.00</td>
<td>0.5</td>
</tr>
<tr>
<td>4</td>
<td>0.5</td>
<td>1.00</td>
<td>0.5</td>
</tr>
</tbody>
</table>

\[ \sum S_i \cdot R_i = 1.25 \]
\[ \sum S_i \cdot R_i / \sum R_i = 1.25/2 = 0.625 = 62.5\% \]
\[ \sum R_i = R_1 + R_2 + R_3 + R_4 = 0.5 + 0.5 + 0.5 + 0.5 = 2 \]

Table 9. Design value for Drain Valve

<table>
<thead>
<tr>
<th>i</th>
<th>( R_i )</th>
<th>( S_i )</th>
<th>( R_i \cdot S_i )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.5</td>
<td>0.25</td>
<td>0.125</td>
</tr>
<tr>
<td>2</td>
<td>0.5</td>
<td>1.00</td>
<td>0.5</td>
</tr>
<tr>
<td>3</td>
<td>0.5</td>
<td>1.00</td>
<td>0.5</td>
</tr>
<tr>
<td>4</td>
<td>0.5</td>
<td>1.00</td>
<td>0.5</td>
</tr>
</tbody>
</table>

\[ \sum S_i \cdot R_i = 1.625 \]
\[ \sum S_i \cdot R_i / \sum R_i = 1.625/2 = 0.812 \]

Rule Viewer
The Rule Viewer also shows how the shape of certain membership functions influences the overall result. Rules shown in Rule Editor provide inference mechanism strategy and producing the control signal as output. In this paper total number of active rules obtained is equal to 25 rules (= 5²) as shown in Fig. The rules are based on “Mamdani Inference Method”. The simulation results are obtained using a 25 rule FLC. Rules shown in Rule Editor provide the control strategy.

4.1 Response of Fuzzy Logic Controller using Rule Viewer
When the value of the level is 0.4 and the rate is 0.09 then the values of control valve and drain valve are 0.62 and 0.826 opened.

These rule viewers provide graphical view of the state of fuzzy logic controller. Each row of plots corresponds to one rule and each column of the plots corresponds to either an input variable (yellow, on the left) or an output variable (blue, on the right). The final output of the system is depicted by red line and is determined by Centroid Rule. Different numbers of rules that used in the system will give the different result, so the analysis for results will be conducted. This system was tested by using different types of methods and membership functions. Rule Viewer of Triangular, Trapezium and Gaussian function in Centroid method are described in figure 12. It has two input variables: Water level=0.4 and flow rate=0.09. The simulated values were checked using MATLAB-Rule viewer as shown in Table 10. By comparing manual calculation, Triangular function (trimf) got the best performance of the result. Moreover, figure also shown calculation accuracy of the fuzzy model is very reasonable.
Table 11. Simulated Values of Control Valve And Drain Valve in Triangular Function

<table>
<thead>
<tr>
<th>Method</th>
<th>Control Valve</th>
<th>Drain Valve</th>
</tr>
</thead>
<tbody>
<tr>
<td>Centroid</td>
<td>0.619</td>
<td>0.826</td>
</tr>
<tr>
<td>Bisector</td>
<td>0.88</td>
<td>0.90</td>
</tr>
<tr>
<td>Mean of Max</td>
<td>0.90</td>
<td>0.90</td>
</tr>
<tr>
<td>Last of Max</td>
<td>0.90</td>
<td>0.90</td>
</tr>
<tr>
<td>Sum of Max</td>
<td>0.90</td>
<td>0.90</td>
</tr>
</tbody>
</table>

Table 10. Comparison of Simulation and Calculated Result

<table>
<thead>
<tr>
<th>Result</th>
<th>Control Valve</th>
<th>Drain Valve</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design Values</td>
<td>62.50</td>
<td>81.25</td>
</tr>
<tr>
<td>MATLAB Simulation</td>
<td>62.00</td>
<td>82.6</td>
</tr>
<tr>
<td>% Error</td>
<td>0.80%</td>
<td>1.6%</td>
</tr>
</tbody>
</table>

4.2 Graphical Discussion

Figure 13 to 17 shows 3-D plot of “Control Valve” and “Drain Valve”. The result of the simulation were displayed by using Rule Viewer in Fuzzy Logic Tool Box in MATLAB programmed. In this design model, the openness of control valve and drain valve depends upon the selected values of water level and flow rate.

5. Conclusion

Hydro power dam have an important role in renewable energy resources. The aim of this control system is to keep the system within the predetermined ranges by controlling the flow through a control valve at the dam and inflow through drain valve in any condition for safely as well as efficient hydro electricity generation. Manual control of reservoir is very difficult in dam because it have nonlinear or time-variable behavior such as sudden changes in reservoir water level. In this paper, an efficient and accurate method based on fuzzy control is proposed for operating system in dam to solve that problem. In this figure, many comparison are figure out by changing...
method such as COA, Bisec, Mom, Lom, Som and change function such as Triangular, Trapezium, Gaussian. In COA method, design model and simulation result are very close using triangular function. By using FLC for control valve and drain valve, it have better stability for water level and flow rate.

Acknowledgments
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